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13. ABSTRACT (Maximum 200 words)

The main objective of this Phase I research is to further develop III-nitride microcavity photonics device technologies. Consistent with our tasks, we have further improved our light emitter output efficiencies by optimizing device layer structures, including superlattice structures for enhancing the hole concentration, the thickness of the top Mg doped p-type layer to reduce the light absorption, and the structure of the active region. We have also carried out preliminary measurements on the size dependence of the micro-size light emitter characteristics, including I-V and L-I characteristics and the transient behavior. It was found that the micro-LEDs were very efficient and the heating effect was not significant in micro-LEDs that are greater than 10 μm. Our results also revealed that the operating speed increases with decreasing micro-LED size and the response time reduced from 0.21 ns for 15-μm LEDs to 0.15 ns for 8-μm LEDs. We have succeeded in fabricating several integrated photonics devices. Their operation under current injection has been achieved and their characteristics remain to be measured. The ability of 2D array integration with advantages of high speed, high resolution, low-temperature sensitivity, and applicability under versatile conditions, make III-nitride micro-LEDs a potential candidate for light sources in short-distance optical communications.

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The main objectives of this Phase I research are to

- Further develop III-nitride microcavity photonic device technologies;
- Demonstrate the feasibility of achieving electrically pumped III-nitride microcavity lasers;
- Assess the feasibility of integrating miniaturized light emitter arrays with waveguides.

The objectives are to be accomplished through the work plan that can be divided into five tasks, which are summarized in Table I.

Table I. Proposed Task Schedule Based on the Month After Receipt of Phase I Award

Tasks	Time, Months								
	Phase I Duration						Optional Duration		
	1	2	3	4	5	6	7	8	9
1. Optimizing μ-cavity emitter materials & structures									
• Blue μ-cavity photonic materials & device structures		□	□	□	□	□	□		
• UV μ-cavity photonic materials & device structures						□	□	□	
2. Optimizing μ-cavity emitter fabrication processes									
• Patterning by lithography and ICP dry etching		□	□	□	□	□	□		
• Self-organization by selective area overgrowth						□	□	□	
3. Characterization of individual μ-light emitters • I-V, L-I, E-L characteristics vs. μ-cavity lateral size; • Polarization and directionality dependence of the lasing spectra; • Turn-on and off speed vs. μ-cavity lateral size; • Operating lifetimes under pulsed and cw injections.	□	□	□	□	□	□	□		
4. Coupling between μ-emitter arrays with waveguides							□	□	□
5. Final Report									□

Consistent with our tasks, we have carried out the following preliminary studies:

1. Further improving blue microcavity photonics device structures.

We have investigated methods for further enhancing the emission efficiency of InGaN/GaN LEDs. The new LED wafers were grown on sapphire substrates with 30 nm GaN buffer layers by low pressure MOCVD. The device structure includes a 3.5 μm of silicon doped GaN, 10 periods of Si doped superlattice consisting of alternating layers of AlGaN (30 Å)/GaN (30 Å), a 0.05 μm of Si doped GaN, two periods of InGaN (30 Å)/GaN (25 Å) undoped quantum well active region. Followed by 14 periods of Mg doped superlattice consisting of alternating layers of AlGaN (30 Å)/GaN (30 Å), and 0.1 μm Mg-doped GaN epilayer. The structure was then thermally annealed at 950 °C for 8 seconds in nitrogen in a rapid thermal-annealing furnace to activate Mg acceptors. By incorporating the modified superlattice structure into the device and decreasing the top Mg-doped p-type layer thickness to 0.1 μm, we have enhanced the power output of our conventional broad area (300 x 300 μm^2) purple LEDs (408 nm) by a factor of 2. Further improvements in materials and structural qualities are needed in order to fabricate microcavity lasers based on these materials.

2. Characterization of micro-size light emitters

III-Nitride Blue Micro-LEDs

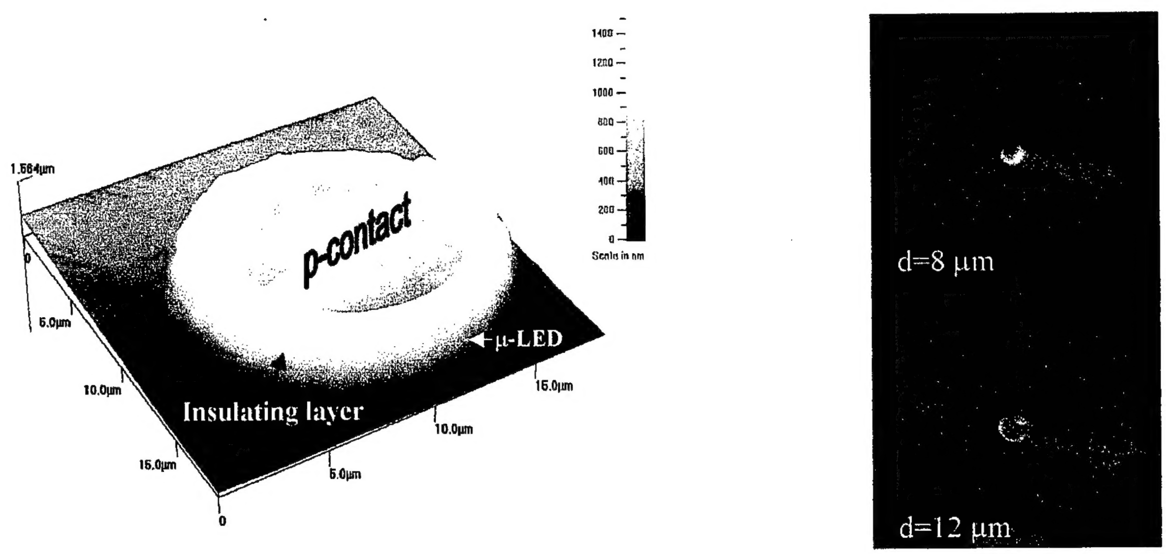

Fig. 1 (a) An AFM image showing a fabricated micro-LED. (b) Optical microscope images of individual μ-disk LEDs in action.

Dring the reporting period, individual μ-disk LEDs of varying diameters from 5 to 20 μm were fabricated by photolithography patterning and inductively coupled plasma (ICP) dry etching. Bilayers of Ni (20nm)/Au (200nm) and Al (300nm)/Ti (20nm) were deposited by electron beam evaporation as p- and n-type Ohmic contacts. The p-type contacts and the n-type contacts were thermally annealed in nitrogen ambient at 650 ^{0}C for 5 min. A dielectric layer was deposited by e-beam evaporation after the μ-LEDs formation for the purpose of isolating p-type

contacts from the etch-exposed n-type layer. This allowed us to carry out preliminary measurements on the size dependence of the μ-LED characteristics. Figure 1 (a) shows an atomic force microscope (AFM) image of a fabricated μ-LED. As can be seen from Fig. 1(a), the p-type contact was connected to the top p-layer by opening a hole through the insulating dielectric layer. The size of the p-type contact is about 4 μm in diameter. Figure 1(b) shows optical microscope images, taking from the top (p-type contact side), of two representative InGaN/GaN QW μ-LEDs with diameters d=8 and 12 μm in action with an injected current of 2 mA. The p-type contacts on the top layers are also visible in Fig. 1(b).

The I-V characteristics of μ-disk LEDs of varying sizes and a conventional board-area LED (300 x 300 μm^2) fabricated from the same wafer are plotted in Fig. 2 (a) linear and (b) semi-logarithmic scales. It is clearly seen that the turn-on voltages for individual μ-LEDs are larger than that of the broad-area LED. Among the μ-LEDs of different sizes, the turn-on voltage increases with decreasing μ-LED size. The slope of the Log I vs. V plot in Fig. 2(b) reflects the ideality factor, n (=1/slope). It is clear that the ideality factor of μ-LEDs (n=18.5) is larger than that of the broad-area LED (n=6.4). There is only a weak size dependence of ideality factor for the μ-disk LEDs. The larger ideality factor reflects the enhanced non-radiative recombination in μ-LEDs, which is most likely a result of enhanced surface recombination around the edge of the disk of μ-LEDs.

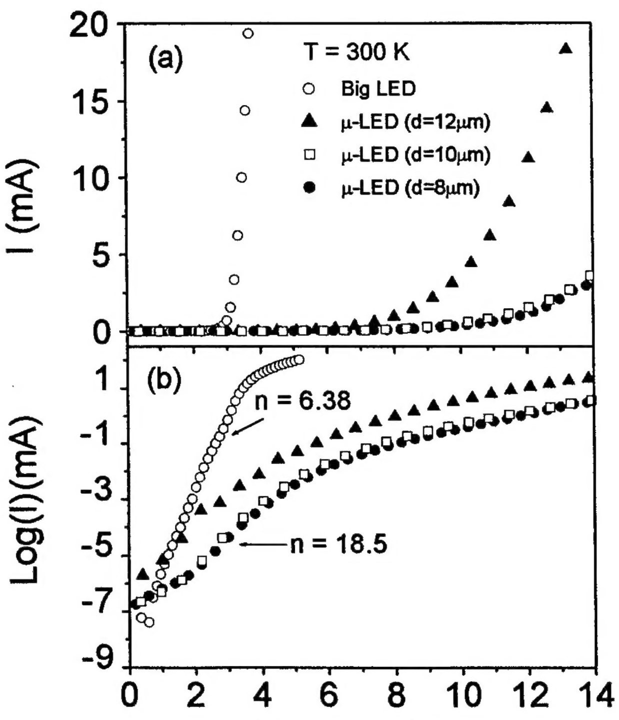

Figure 2 I-V characteristics of μ-LEDs of varying sizes (d =8, 10, and 12 μm) and a broad-area LED (300 x 300 μm^2) in (a) linear and (b) semi-logarithmic plots.

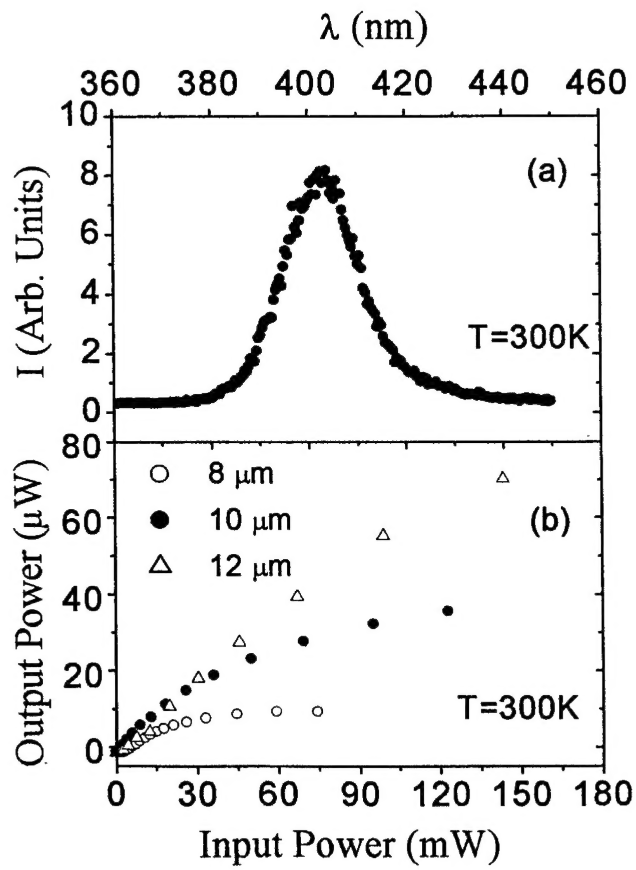

Figure 3 (a) E-L emission spectrum of a purple μ-LED. (b) Output power vs. input power (L-I) plot of μ-LEDs of different sizes.

Figure 3 shows a room temperature electro-luminescence (EL) spectrum of a purple μ-LED measured at a forward current of 2 mA. Fig. 3(b) plots the output power vs. input power measured from the sapphire substrate side for three unpackaged μ-LEDs of different sizes. Heating effects become more prominent as the size of μ-LEDs decreases. For μ-LEDs with d=12 μm, the output power increases almost linearly with input power in the entire measured range. However, for μ-LEDs with d=8 μm, the output power saturates at about 10 μW for input power above about 45 mW. As expected, heat dissipation is more difficult in μ-LEDs with reduced sizes, which causes power output saturation. However, we believe that appropriate packaging processes can improve the performance.

Transient Responses of III-nitride μ-LEDs

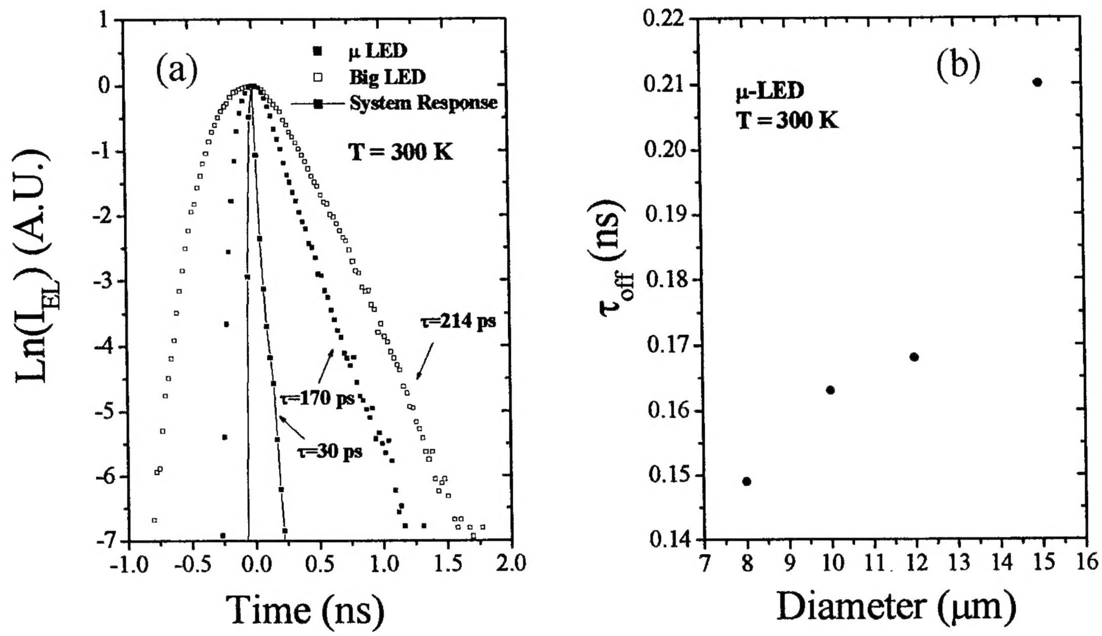

Fig. 4 (a) Transient responses of a microdisk LED of 12 μm in diameter and a broad-area LED (300 x 300 mm2) in response to picosecond electrical pulses. The turn on time of the microdisk LEDs is on the order the system response (< 35 ps). (b) The size dependence of the turn-off time of the microdisk LEDs. τ_{off} decreases with a decrease of μ-LED size. It reduced from 0.21 ns for d=15 um to 0.15 ns for d=8 um.

These μ-LEDs have potential applications in short distance optical communications. For these applications, the speed is one of the most crucial parameters, which has been measured by time-resolved EL. In Fig. 4 we plotted (a) transient responses of a μ-LED and a conventional broad-area LED and (b) the size dependence of the "turn-off" time, τ_{off}, of μ-LEDs. The turn-on response was very fast and could not be measured. However, the turn-off transient was in a form of single exponential and its lifetime, τ_{off}, could be determined. It was found that τ_{off} decreases with a decrease of μ-LED size. It reduced from 0.21 ns for d=15 μm to 0.15 ns for d=8 μm. This behavior is also expected since the effects of surface recombination are enhanced in smaller μ-LEDs. On the other hand, the increased operating speed may also be a result of an enhanced radiative recombination rate in μ-LEDs. With this fast speed and other advantages such as long

operation lifetime, III-nitride μ-LED arrays may be used to replace lasers as inexpensive short distance optical links such as between computer boards with a frequency up to 10 GHz.

3. <u>Fabricating novel μ-light emitter structures and studying the coupling between μ-structures</u>

We have succeeded in fabricating double-ring μ-cavity light emitters. As illustrated in Fig. 5, their operation under current injection has been achieved. These novel light emitter structures will be utilized to study the mechanisms of coupling between μ-size light emitters. The directionality and polarization of the emission and the optical efficiency and resonant modes behaviors will be measured and compared for different sizes/structures. Other integrated μ-structures, such as emitter-emitter and emitter-waveguide will also be fabricated for these studies.

III-Nitride Double-Ring μ-Cavity Light Emitters

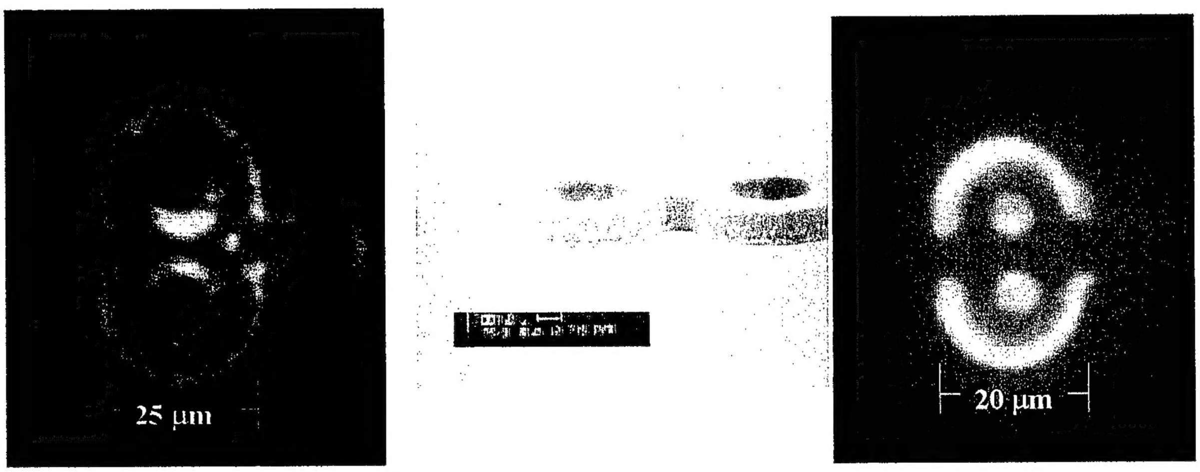

Fig. 5 Optical microscope images of III-nitride double-ring microcavity emitters under operation. Center: Scanning electron microscopy (SEM) image of a double-ring microcavity emitter prior to electrical contacts fabrication.